Factors Influencing Shelter in the Woodhill Protection Strip

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Bachelor of Forestry Science

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Abstract

Woodhill Forest, situated on the west coast of the Auckland region, is directly exposed to strong westerly winds coming from the Tasman Sea. To protect the 41km long *Pinus radiata* forest, a protective strip of trees has remained unharvested between the coast and the remaining forest. The protection strip plays a valuable role in sheltering the forest against strong, salt-laden winds. The aim of this research was to investigate the shelter provided to the production forest by the protection strip.

The protection strip was mapped using aerial imagery. A site was selected where measurement of the protection strip and the production stand immediately adjacent could be undertaken. Protection strip height, basal area, width, health, and crown length were measured at three plots along 24 transects. Production stand volume was measured at three plots at even intervals along the same transects. Regression analysis was used to assess the relationship between protection strip variables and production stand volume at 20m, 90m, and 170m from the protection strip.

The analysis showed that height (adjusted for the elevation difference between the protection strip and the stand) (r=0.56), and the health (r=0.41) of the inland edge of the protection strip were significantly correlated with volume within the first 20m of the stand. The two variables were multiplied together to create a shelter variable which had a significant correlation with stand volume at 20m (r=0.65), and at 90m (r=0.42) away from the strip. When confounding effects of site influence were controlled, the shelter was still deemed to have a significant relationship with stand volume, providing confidence that the relationships detected were not only the result of underlying site conditions. The shelter variable was significantly correlated with distance to the coast (r=0.50).

Despite the relationship between the shelter variable and distance to the coast, the protection strip width did not show a significant relationship with stand volume. It can be concluded that the protection strip can provide sufficient shelter when as narrow as 280m wide, the minimum width tested during this investigation.

These results provide an indication as to how to assess the quality of the protection strip and the key factors to consider when the protection strip is maintained or replaced in the future. They also provide some indication on how to improve the protection strip to achieve greater forest productivity.

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Chapter 1: Introduction

1.1 Background

Woodhill Forest is a *Pinus radiata* forest planted on coastal sand dunes which extend from Muriwai to the South Head of the Kaipara Harbour in the Auckland region, New Zealand (Figure 1.1). A forest was initially established at the site to stabilise the drifting sand dunes as they encroached on productive farm land to the east (McKelvey, 1999). Using a method of successional planting recommended by Cockayne (1911), *Ammophila arenaria* (marram grass), *Lupinus arboreus* (lupine), and finally *P.radiata* were planted to create a forest over three decades. The first *P.radiata* trees were planted in 1936 (McKelvey, 1999). Since then the forest has been managed by various organisations and in 2013 Woodhill Forest was returned to Ngā Maunga Whakahii o Kaipara (NMWoK), representing the Ngāti Whātua o Kaipara iwi. In 2015 NMWoK entered a joint venture with Rayonier Matariki Forests (RMF) to manage the subsequent rotations of trees.

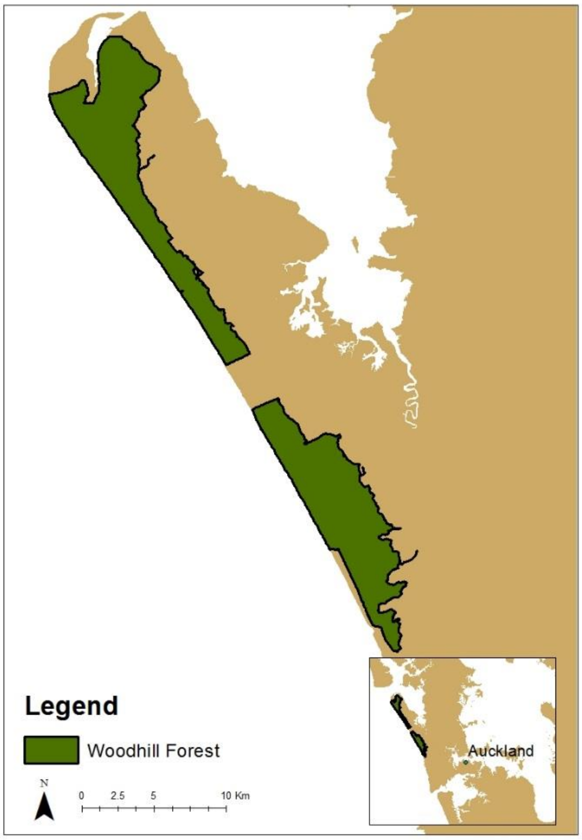

Figure 1.1: Location of Woodhill Forest

Currently Woodhill Forest is a 12,500ha *P.radiata* forest utilised for recreational purposes, filming locations, and productive forestry. The forest is long and narrow, stretching 41km along the coast and is 7.6km at its widest point. It is divided into two halves by a separate forestry block in the middle. The forest is parallel to the Tasman Sea and it is directly exposed to any strong, salt-laden winds coming from the west. Trees close to the coast have previously been reported to be killed or deformed by both strong westerly winds and the corresponding salt deposition (Berg, 1972). As protection from the damaging effects of coastal exposure, the stands adjacent to the coast were excluded from harvesting and left to shelter the remaining forest (Berg, 1972), creating what is referred to as the protection strip, seen in Figure 1.2.

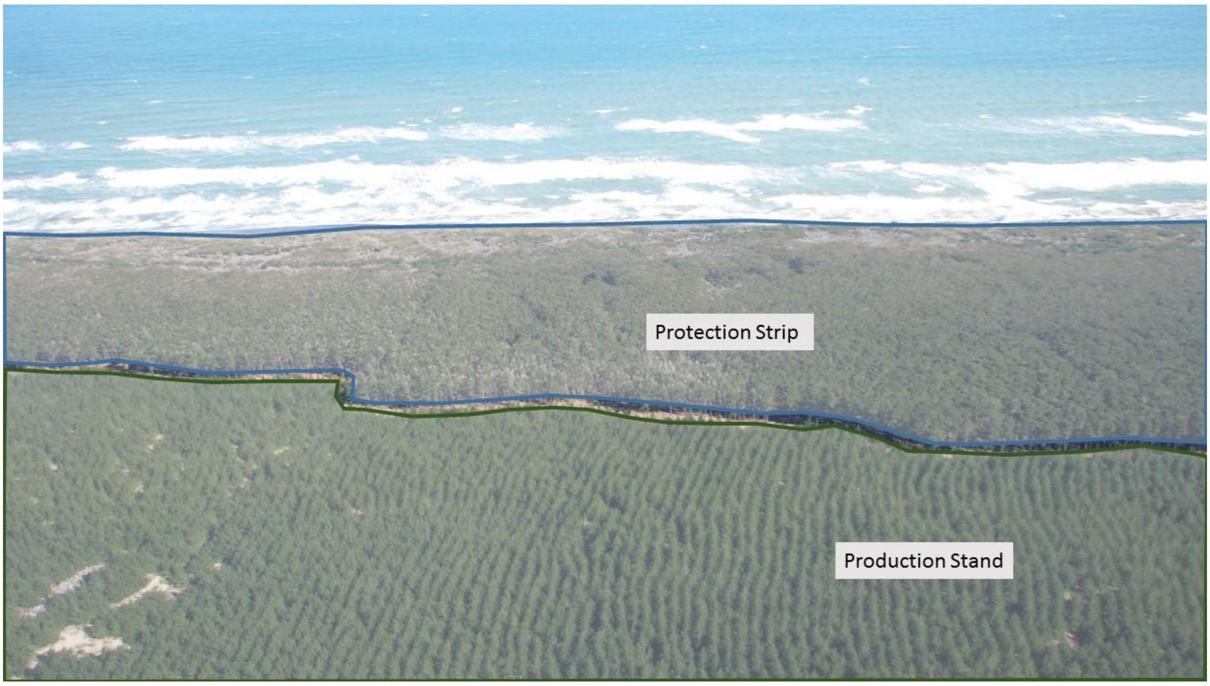

Figure 1.2: Arrangement of the protection strip and production stand in Woodhill Forest.

1.2 Purpose

The trees in the Woodhill protection strip were not planted for the specific purpose of sheltering the rest of the forest. It is therefore unlikely that the protection strip is optimal for maximising production within the forest. The age and condition of the protection strip also suggests that the effectiveness of the protection strip will decline in the future. Management decisions will need to be made in regard to the maintenance and replacement of the protection strip to ensure the continued success of Woodhill as a production forest. Neither NMWoK nor RMF have extensive experience in managing Woodhill Forest and require more knowledge on the protection strip and the degree to which it shelters against coastal exposure before sound management decisions can be made.

The only other research undertaken to improve the shelter provided in Woodhill Forest focused on species selection (Berg, 1972). Although there are other examples of similar coastal forests in New Zealand (e.g. Auporui Forest in Northland and Waitarere Forest in Horowhenua), there appears to be no documented process for providing shelter to the tree crop from coastal processes in any of these forests. The lack of comparable examples to Woodhill Forest compounds the difficulties on making important management decisions.

The purpose of this study is to provide some of the information required to help make an ongoing management plan for the Woodhill protection strip. Establishing what aspects of the Woodhill protection strip are most important to maximise growth in the production forest behind will allow for informed management decisions to be made. Both NMWoK and RMF would benefit from maximising production in the Woodhill Forest and increasing productivity may be possible by improving shelter or increasing net stocked area of the forest.

1.3 Research Questions

The primary aim of this research is to investigate the shelter provided to the production stand by the protection strip in Woodhill Forest. To do so, the investigation will be guided by the following questions:

- Is production stand volume related to characteristics of the protection strip?
- Is production stand volume related to the width of the protection strip?
- How can the quality of the protection strip be assessed?

Chapter 2: Literature Review

Shelterbelts interact with the environment around them. The primary function of a shelter belt is to improve conditions for buildings, livestock, orchards, and crops (Woodruff & Zingg, 1953). Shelterbelts primarily provide shelter by exerting a drag force on wind flow which results in a reduction of wind speed (Wang & Takle, 1997). The area downwind from a shelterbelt, reported in multiples of shelterbelt height (H), is thus protected to some degree against the wind. Shelterbelts have also been used to alter the local microclimate (Campi, Palumbo, & Mastrorilli, 2009) and provide shelter against air-borne salt (Zhu, Gonda, Matsuzaki, & Yamamoto, 2002). The services that a shelterbelt provides can directly influence the productivity of the crops downwind (Sudmeyer & Scott, 2002). The influence on productivity has been long known, and many attempts to provide details on the "optimum" shelterbelt has been attempted over the years. Shelterbelt studies have focused on the size, shape and interior structure of the shelterbelt to give insight on how these aspects influence the downwind shelter.

Two distinct approaches have been taken in assessing downwind shelter and its implications on productivity. Studies have either measured the influences of natural shelterbelts in field experiments (e.g. McAneney, Salinger, Porteous, & Barber (1990)) or have employed the use of wind tunnels and numerical models to simulate the effects of a shelterbelt (e.g. Bitog et al. (2012)). Shelterbelts have typically been considered in the context of agricultural and arable scenarios (e.g. Hawke & Tombleson (1993)), while research for horticulture purposes have also been completed (McAneney, Judd, & Trought, 1984). Aside from work by Berg (1972) in Woodhill Forest, the reviewed literature provides no examples of a shelterbelt being used to protect other trees. Despite the lack of examples, it has been assumed that a production forest would respond to the effects of shelter and microclimate similar to that of other production crops.

2.1 Shelterbelt Effects

2.1.1 Wind protection

Shelterbelts have been employed to create areas of reduced wind speed where either constant or strong winds have a negative impact on downwind crops or objects. Wind speed is able to be reduced to almost 0m/s depending on shelterbelt design (Cornelis & Gabriels, 2005), and the influence of this can extend over 30H (Caborn, 1957). A reduction in wind speed can be seen in growth patterns of plants with damage on *Actinidia chinensis* (kiwifruit) found to have a direct relationship with distance downwind from a shelterbelt (McAneney et al., 1984). The minimum wind speed behind a shelterbelt is typically found somewhere between 5H and 8H downwind (Cornelis & Gabriels, 2005; Wang & Takle, 1996).

Shelter provided by a shelterbelt is variable in the vertical as well as horizontal dimension. Although the differences are not large, the effectiveness of a shelterbelt changes depending on the height where shelter is measured (Caborn, 1957). The greatest wind speed reduction occurs at a height less than half the height of the shelterbelt (Woodruff & Zingg, 1953) and wind speed will be greater at the same height as the shelterbelt than it is at ground level (Caborn, 1957). Due to wind flow being deflected over the shelterbelt, the wind speed can be greater above the shelterbelt than unsheltered areas (Woodruff & Zingg, 1953).

2.1.2 Microclimate

Shelterbelts have also been frequently utilised to adjust local microclimate conditions in production settings. However, the reports on the effects of shelterbelts on microclimate can be variable. Some research suggests that daily mean air temperature was not impacted by the presence of a shelterbelt (Sudmeyer & Scott, 2002), while other studies found a noticeable increase in both air and soil temperature (McAneney et al., 1990). Water availability can also be impacted. Soil water close to a shelterbelt (within 3H) was reported to have significantly lower levels than areas beyond this region, attributed to competition from trees in the shelterbelt (Hall, Sudmeyer, McLernon, & Short, 2002). However, in years of drought shelterbelts were found to reduce the levels of soil evaporation beyond 3H and as far as 20H downwind from a shelterbelt, increasing soil moisture compared to unsheltered areas (Hall et al., 2002).

2.1.3 Salt protection

Where shelterbelts and forests are adjacent to the coast they can play an important role in preventing particles of wind-driven salt causing damage further inland. Salt concentration in coastal wind is dependent on wind speed when the velocity it greater than 5m/s (Lewandowska & Falkowska, 2013; Zhu et al., 2002). Shelterbelts can reduce salt concentration by reducing the wind speed (Zhu et al., 2002) and by filtering salt particles through the crown (Potts, 1978; Zhu et al., 2002). The concentration of sea salt has been found to be significantly lower inside a forest than outside (Potts, 1978; Zhu et al., 2002), and is further reduced with increasing distance into a forest as far as 3H (Potts, 1978). Despite the forest canopy having a significant ability to hamper the inland progress of air-borne salt, the understory has less of an impact. Salt concentration under the canopy has been found to be independent of stem density (Zhu et al., 2002).

The damage caused by salt can be significant in coastal forests. Within the first 5m of a coastal exposed forest, *Picea sitchensis* (Sitka spruce) trees have been observed to have a reduced height, yellowing needles, and higher mortality of young shoots (Potts, 1978). Similarly, air-borne salt can also have a negative impact on *P.radiata* with Berg (1972) observing all trees within 100m of the dune top in Woodhill Forest experiencing salt burn despite *P.radiata* growing in coastal areas in its native range (Forde, 1966).

2.1.4 Crop production

Shelterbelts are used to provide protection on productive land with the intention to improve crop performance. Productivity of pasture and arable crops behind a shelterbelt can be categorised into three zones: an area of low productivity directly adjacent to the shelterbelt, an area further downwind where productivity is increased, and an area where the influence of the protection strip is negligible (Campi et al., 2009). Within 3H of a shelterbelt, productivity of pasture and arable crops is consistently lower than unsheltered areas due to the competition for resources within the root zone of trees in the shelterbelt (Campi et al., 2009; Sudmeyer & Scott, 2002; Sun & Dickinson, 1994). Where this area of restricted resources ends, crop productivity can be expected to be higher than in unsheltered areas with improved microclimate conditions and less wind induced damage (Campi et al., 2009; McAneney et al., 1990; Sun & Dickinson, 1994). Where the sheltering influence of a shelterbelt dissipates productivity will no longer be impacted by the shelterbelt (Campi et al., 2009; Sudmeyer & Scott, 2002; Sun & Dickinson, 1994). Whether the net result of these different zones is an overall increase in productivity varies with studies. Hawke & Tombleson (1993) found an overall decrease in productivity, while Campi et al. (2009) and Sun & Dickinson (1994) reported the opposite. The impact on productivity can depend on climatic conditions and effects of wind. A shelterbelt was only deemed economically justifiable when unsheltered areas where experiencing water stress (Sudmeyer & Scott, 2002) or the effects of wind damage (Hall et al., 2002).

2.2 Shelterbelt Design

2.2.1 Width

Shelterbelt width can be highly variable, both between and within examples. Natural shelterbelts can be as narrow as one tree width, while there is no physical limit on how wide they can be. In extreme examples, shelter fences act as a two-dimensional barrier against the wind (Perera, 1981), while there are examples of entire forests acting to provide shelter (Zhu, Gonda, Matsuzaki, & Yamamoto, 2003). Shelterbelt width is an important consideration as where width extends too far, the loss of productive land can nullify the impacts of any improvement in plant performance (Wang & Takle, 1996). However, shelterbelt width can influence the size of the area sheltered and the degree of shelter provided. As a shelterbelt width increases the location of the maximum wind speed reduction moves closer to the belt (Caborn, 1957; Wang & Takle, 1996; Yusaiyin & Tanaka, 2009). In narrow shelterbelts (where width is less than 5H) the differences in width has little effect on downwind shelter (Wang & Takle, 1996). The area behind a shelterbelt where the wind speed is reduced by at least 20% is shorter for wider shelterbelts than for narrower counterparts (Wang & Takle, 1996). The influence of width on shelter is negligible by 30H (Wang & Takle, 1996).

2.2.2 Height

Almost all reviewed literature expressed the distance of shelter provided by a shelterbelt in units of tree height. This suggests that the shelter provided is a direct function of shelterbelt height; however, very little evidence was provided on the exact relationship between structure height and shelter provided. McAneney et al. (1990) did report that the daily volume of wind in the lee of a shelterbelt had a strong, negative, and linear relationship with shelterbelt height. An increase in the shelter effect can be explained by a greater drag force enacting upon wind flow with increasing height, causing a reduction in wind speed (Wang & Takle, 1997).

2.2.3 Porosity

Shelterbelt porosity is the ratio of pore space to space occupied by vegetation (Cornelis & Gabriels, 2005). The terms density and optical porosity (the percentage of open space from a side view of the shelterbelt (Zhou, Brandle, Mize, & Takle, 2005)) are terms frequently substituted for true porosity. Porosity has been attributed as one of the most important shelterbelt aspects and plays an important role in downwind wind speed reduction (Cornelis & Gabriels, 2005) as it impacts both the degree to which wind speed is reduced and the distance where shelter is provided down wind. Increasing the porosity of a shelterbelt, or decreasing the density, will decrease the ability for the shelterbelt to reduce wind speed but will increase the distance where it is reduced (Bitog et al., 2012; Perera, 1981; Wang & Takle, 1997).

Although Perera (1981) struggled to conclude an optimum level of shelterbelt porosity, other studies have stated that a medium level of porosity will provide the best downwind shelter. Medium porosity shelterbelts are more efficient than high porosity shelterbelts as a higher density increases the drag enforced on wind flow (Wang & Takle, 1997). However, low porosity shelter belts allow for a more uniform wind speed across the shelterbelt, resulting in a more rapid recovery of wind speed and a shorter shelter distance (Wang & Takle, 1997). Cornelis & Gabriels (2005) concluded a porosity between 20% and 30% was optimal for creating downwind shelter.

2.2.4 Shape and structure

Shelterbelts can be shaped and structured into many designs. The shape and structure can influence the shelter pattern downwind of a shelterbelt. In particular, the angle of the windward edge of a shelterbelt can affect how wind speed is reduced. A long, shallow slope of the shelterbelt margin reduces the length where the wind speed is diminished (Caborn, 1957; Woodruff & Zingg, 1953). A slope enables the wind to be deflected over the top of the shelterbelt rather than allowing some wind to pass through the shelterbelt, thus the effect of slope is similar to that of decreasing porosity (Caborn, 1957). The more the acute angle, the more pronounced the effect of slope will be (Caborn, 1957). However, the influence of slope only produces small differences in wind speed reduction (Caborn, 1957; Woodruff & Zingg, 1953). The wind speed reduction behind a shelterbelt with a 30° slope was only 10% less than a shelterbelt with a 45° slope (Caborn, 1957).

2.3 Shelterbelt Measurement

Height and width, key shelterbelt variables, are measurable with simple techniques. Porosity, also deemed to be an important attribute of shelterbelts, has proved to be more difficult to measure. Many studies have attempted to find variables which can either accurately predict porosity, optical porosity, or be substituted for porosity when explaining wind speed reduction. Photo silhouettes is the most commonly used method of obtaining porosity estimates and can be used to explain high degrees of wind speed reduction (Loeffler, Gordon,

& Gillespie, 1992; Řeháček, Khel, Kučera, Vopravil, & Petera, 2017; Zhu et al., 2003). However, this is only a suitable technique for shelterbelts consisting of only one or two rows of trees.

Optical porosity can be an inappropriate measure for wide shelterbelts, where the structure should be considered in three dimensions (Torita & Satou, 2007). The problem of estimating shelterbelt porosity has led to several attempts in providing alternative measurement techniques for wide shelterbelts. Lee, Ehsani, & Castle (2010) proposed the use of a vehicle mounted lasers to accurately measure tree canopy geometry in shelterbelts. Although this study was able to explain over 90% of wind speed reduction, it did not test the technique on large scale shelterbelts and the practicality is limited by the availability of technology. Remote sensing has been found to be able to provide a variable highly correlated with shelterbelt porosity (Yang, Yu, & Fan, 2017). Multispectral satellite imagery can be processed to provide variables including Leaf Area Index (LAI) and crown length (Yang et al., 2017). Yang et al. (2017) suggested a formula to provide a highly correlated variable for shelterbelt porosity using these variables.

$$\text{Porosity} = 1.829 \times (\text{Crown Length} \times \text{LAI} \times \text{Width})^{-0.404} \quad (1)$$

Other research has attempted to find variables which can explain downwind shelter. A medium proportion of large trees has been found to relate to a longer shelter length (Wu et al., 2013). Wu et al. (2013) also found that a high basal area increased the level of wind speed reduction; however, this could be explained by a decreasing porosity. Field measurements of a range of species, including other *Pinus* spp. have shown that total vegetation per unit of ground area, multiplied by shelterbelt width is able to be used as an indicator of wind speed reduction (Torita & Satou, 2007).

The findings presented in this literature review have been determined though field studies, models, and simulations. Although wind tunnels and numerical models are better at isolating the aspect in question (Caborn, 1957), they have limitations in the ability to truly represent dynamic, tree shelterbelts. Model shelterbelts used in wind tunnel experiments typically substitute trees with nails or sticks, which remove the influence of tree branches and tree movement in any effects on wind flow (Cornelis & Gabriels, 2005). Similarly, numerical models of shelterbelts, such as that undertaken by Wang & Takle (1997) require the assumption that the solid elements are motionless. However, Caborn (1957) investigated shelterbelts using wind tunnels before comparing results with field measurements, finding models accurately simulated the wind speed around natural wind breaks.

2.4 Conclusions

The ability of a shelterbelt to act as a barrier against wind has clear impacts on the downwind environment. The drag force created by a shelterbelt creates a pattern of altered wind speed (Wang & Takle, 1997) which can reduce damage to crops and alter the downwind microclimate. In the case of coastal exposed areas, shelterbelts are able to reduce the concentration of air-borne salt (Potts, 1978; Zhu et al., 2002), which has been shown to impact coastal forests (Berg, 1972). It is these effects which have influenced the decision to utilise shelterbelts on productive land, such as the one seen at Woodhill Forest. However, shelterbelts are not always found to significantly influence crop yield (Sudmeyer & Scott, 2002). It is therefore important to understand how the shape and structure of a shelterbelt influence the shelter provided and the response of the protected crop.

Where the intended purpose of the shelterbelt is to protect and influence growth of productive crops, the direct measure of the structure and the crops behind is common (e.g. Campi et al., (2009)). The response of a crop encompasses the influence of wind speed, microclimate, and salt protection. The literature suggests that shelterbelt width, height, density, cross section profile, and crown length are all able to provide some explanation on downwind shelter and the productivity of protected crops.

Chapter 3: Methodology

The literature demonstrated that shelterbelts adjust the growing conditions as far as 30H downwind of the barrier. Adjustments can have an influence on the growth patterns of sheltered plants. Potential determinants of shelter from the Woodhill Forest protection strip include: height, width, density, shape, LAI, and crown length. The literature also demonstrated that the response of downward crops can be variable depending on the distance from the shelterbelt. The following study was designed to capture the influence of stand characteristics and the pattern of forest growth directly behind the protection strip. To minimise the impacts of stand age and management decisions, stand measurements were only taken in one stand.

3.1 Mapping

The protection strip was mapped using aerial imagery to provide information on size and composition. Areas of different vegetation cover within the protection strip were digitised and classified into the following categories:

- Forest
- Grass
- Unvegetated

Mapping utilised aerial photography taken in 2015 and Sentinel-2 satellite imagery from 20/11/2017 provided by the European Space Agency (ESA) (European Space Agency, 2017b). The aerial and satellite imagery were used in conjunction to provide both high temporal and pixel resolution.

The size of the protection strip was calculated from the mapped area. Protection strip width was found using width measurements placed at 10m intervals along the length of the protection strip. Measurements were made perpendicular to the coast edge, at a bearing of 58°.

LAI values for the protection strip were calculated from the sentinel satellite imagery. The imagery was processed using ESA Sentinel Application Platform (SNAP) Biophysical Parameters tool (European Space Agency, 2017a). The tool uses an algorithm to process bands: B3, B4, B5, B6, B7, B11, and B12 to provide an estimate of LAI per 10m x 10m pixel for the entire forest (Figure 3.1). The LAI values were used to provide an average LAI per plot. The use of sentinel satellite imagery to calculate forest LAI has been found to provide estimates, on average, within 8% of measured values (Stankevich, Kozlova, Piestova, & Lubskyi, 2017).

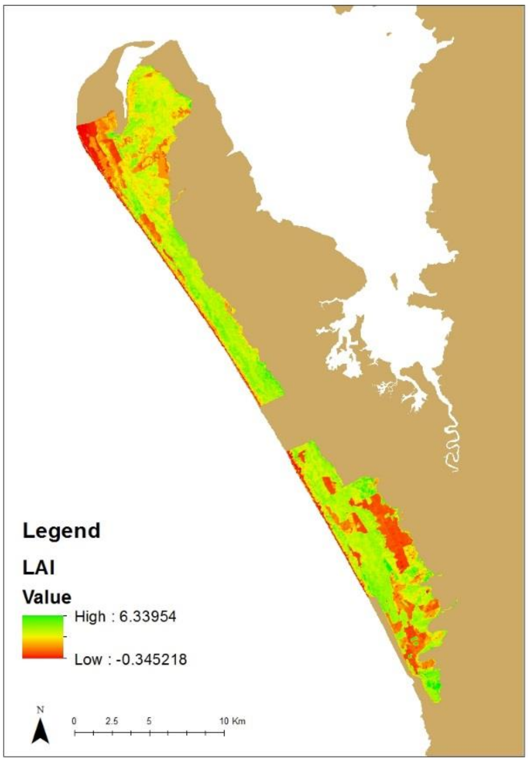

Figure 3.1: Map of LAI values in Woodhill Forest derived from Sentinel-2 satellite imagery

3.2 Site

A site to undertake protection strip sampling was selected. Stand R02, a 48.3ha *P.radiata* stand established in 2002, and the protection strip adjacent to the stand was selected for measurement. This site was selected as the stand had the longest boundary with the protection strip of any appropriately aged stand, with width suitable for sampling. The geographic location of the stand is 36°35’20”S, 174°15’30”E (Figure 3.2). According to information received from Hancock Forest Management (P.Houston, personal communication, January 16, 2018), the stand was initially planted at 555 stems/ha but has since been thinned.

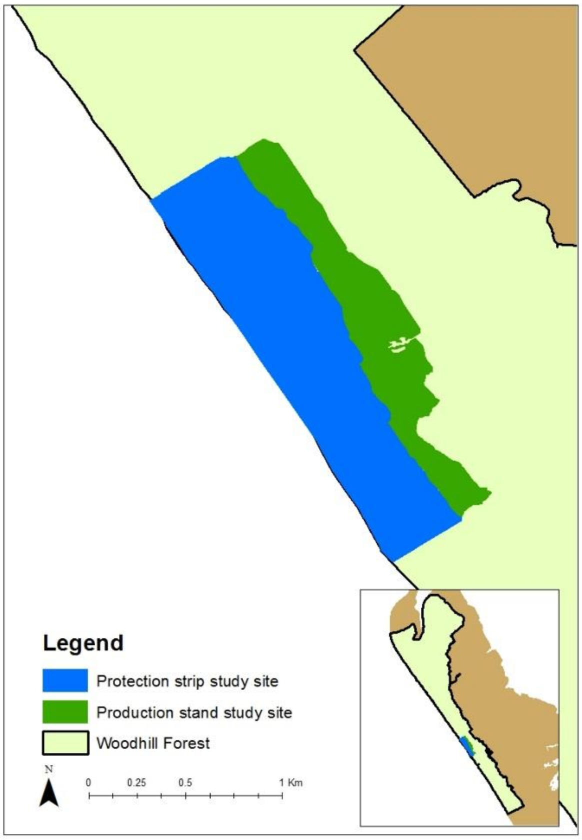

Figure 3.2: Location of the production stand and protection strip used for measurement

According to stand records, the protection strip at the study location was of variable age, between 35 years and 51 years (P.Houston, personal communication, January 16, 2018). The strip primarily consists of *P.radiata*; however, a row of *Cupressus macrocarpa* (macrocarpa) was present along the entire length, within 100m of the coastal edge. Furthermore, *Cortaderia selloana* (pampas grass) is a common understory species throughout the forest.

According to historic climate records (1981-2010), the median annual rainfall at Woodhill Forest is between 1,000 mm/year and 1,200mm/year and the median annual average temperature is between 15°C and 16°C (NIWA, 2012). Although no information on wind speed was given, the median annual average wind speed was estimated to be between 4m/s and 5m/s.

3.3 Protection Strip and Stand Measurement

The protection strip and production stand were measured using plots along 24 transect lines. Transect lines ran from the coast edge, through the protection strip, to the far edge of the production stand behind. Transects were placed perpendicular to the coast, at a bearing of 58°. Six plots were placed along each transect, three plots were in the protection strip and three were in the stand behind. The three plots in the protection strip were evenly spread between the strip edges to provide details on changes in the strip with distance from the coast. Figure 3.3 shows how the plots were arranged between the protection strip and the production stand.

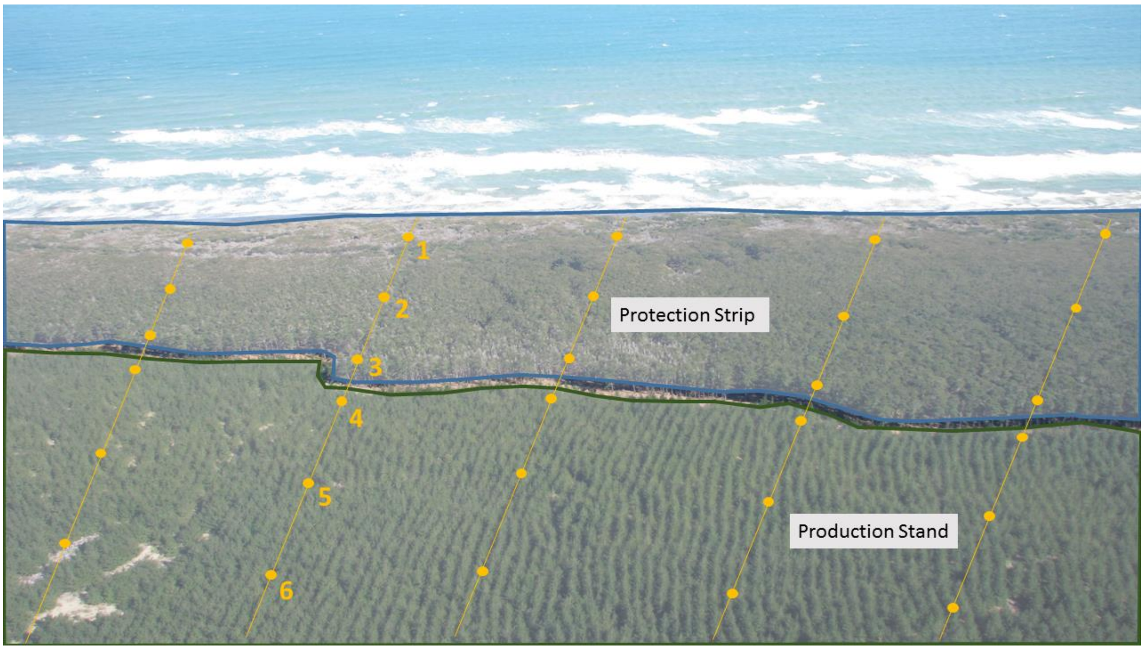

Figure 3.3: Example of how the transects and plots were arranged in the protection strip and in the production stand

Plots in the protection strip (plot 1 to plot 3) were circular and 0.03ha in size. In the plot predominant tree height (PMH), tree diameter at breast height (DBH) and crown length were measured. PMH was defined by (Goulding, 1995) as *"The average height of the tallest tree, free of malformation, in each 0.01ha plot"*. To measure PMH, each plot was divided into even 0.01ha wedges, with the first tree measured for DBH used as the starting point for dividing lines. The tree in each section with the largest DBH was deemed to be the tallest tree, unless there was reason to suggest another tree within the plot section was taller, in which case that tree would be used. Tree heights were measured using a vertex hypsometer. DBH of every tree was measured at 1.4m from the ground using a diameter tape. Where trees were forked below 1.4m, both stems were measured. Trees measured for PMH were also measured for crown length. Crown length was also measured with a vertex hypsometer. Crown length was deemed to be the distance between where constant green branching occurred and the top of the tree. Each tree was given a health rating. The rating was a subjective judgement of whether the tree was healthy, poor or dead according to the amount of green crown visible. An example of each tree rating can be seen in Figure 3.4. Due to the small tree size and high stocking rate caused by multi-stemming of trees in the first plot of each transect in the protection strip, only tree height was measured in these plots. This allowed for the protection strip shape to be estimated.

Figure 3.4: Examples of trees rated healthy, poor and dead at Woodhill Forest.

In the production stand, plot 4 to plot 6 in each transect were spaced at even intervals away from the protection strip. Plot 4 was located 20m from the strip edge, plot 5 and 6 were placed at 70m intervals thereafter. The production stand was between 340m and 90m wide. Measuring at a maximum of 160m from the protection strip provided enough area for transects to be placed within the stand. Plots 4 to 6 were circular and 0.04ha in size to reflect the lower stocking in the stand. The DBH and health rating for all trees were recorded, along with the height of the 4 largest trees to calculate PMH. Table 3.1 describes the plot locations and measurements taken of the six plots.

Table 3.1: The location and measurements taken in the 6 plots of each transect

	Plot	Location	Measurements
Protection strip	Plot 1	50m from coast edge	Tree Height
	Plot 2	Midpoint between Plot 1 and 3	PMH, DBH, Crown Length, Health Rating
	Plot 3	20 in from inland edge	PMH, DBH, Crown Length, Health Rating
Production stand	Plot 4	20m from protection strip	PMH, DBH, Health Rating
	Plot 5	90m from protection strip	PMH, DBH, Health Rating
	Plot 6	160m from protection strip	PMH, DBH, Health Rating

The transects were placed along the stand, with a distance no closer than 35m between each. No transects were placed where the production stand was less than 175m wide. Plot location was predetermined and located using a hand-held GPS. The average elevation for each plot was calculated using a digital terrain model. Field measurements were undertaken at two different times, between 8/1/2018 and 2/2/2018, and between 9/4/2018 and 13/4/2018.

3.4 Data Analysis

3.4.1 Tree volume

Volume of trees within the production stand were calculated and aggregated to create plot averages. A height-diameter relationship was produced using all trees measured for height in plot 4, 5 and 6 (Appendix 1). Tree heights for all trees were calculated. Volume function 183 (Formula 2), specific to Woodhill Forest, was used to derive tree volumes.

$$\text{Tree volume} = DBH^{a} \times (Ht^2/(Ht-1.4))^{b} \times \exp(c) \qquad (2)$$

Where,

- DBH is tree diameter at breast height
- Ht is tree height from the height-diameter relationship
- a = 1.806523
- b = 1.369037
- c = -11.0107

3.4.2 Heath score

A health score value was calculated for each plot (Formula 3). The health score is a variable between 0 and 1 used to indicate the condition of trees within a plot, based on the health ratings recorded during sampling. Healthy, poor, and dead trees were given a weighting of 1, 0.1, 0.02 respectively. Weights were determined though an iterative process to determine what weighting provided the best relationship with stand volume.

$$\text{Health score} = (h + p \times 0.1 + d \times 0.02) / (h + p + d) \quad (3)$$

Where,

- h is count of healthy stems per plot
- p is count of poor stems per plot
- d is count of dead stems per plot

3.4.3 Shelter variable

Liner regression analysis was used to estimate the strength of the relationship between key shelter variables and the volume of each of plot 4, 5, and 6. A single variable was calculated to best predict stand volume using plot 3 PMH, with the difference between elevation of plot 3 and the appropriate plot removed, and the health score (Formula 4).

$$\text{Shelter} = (\text{Plot 3 PMH} + (\text{Plot 3 Elevation} - \text{Plot X Elevation}) \times \text{Plot 3 Health Score} \quad (4)$$

- Where Plot X Elevation is the elevation of the plot in question

Chapter 4: Results

4.1 Protection Strip Dimensions

The total area of the protection strip was measured to be 1,563ha, accounting for 13% of the total forest area. Figure 4.1 shows the distribution of measured widths of the protection strip. A large variation in protection strip width was detected. At its narrowest point, there was only 29m of protection strip between the coast and the production forest. At the widest point, this extended to over 480m. The mode of strip width was found to be 268m, and the median was 266m. The grey bars in Figure 4.1 show the distribution of width of the study site. The width of the study site was at the high range of the protection strip width distribution, varying from 249m to 483m. The mode of the measured widths was 408m and the median was 363m.

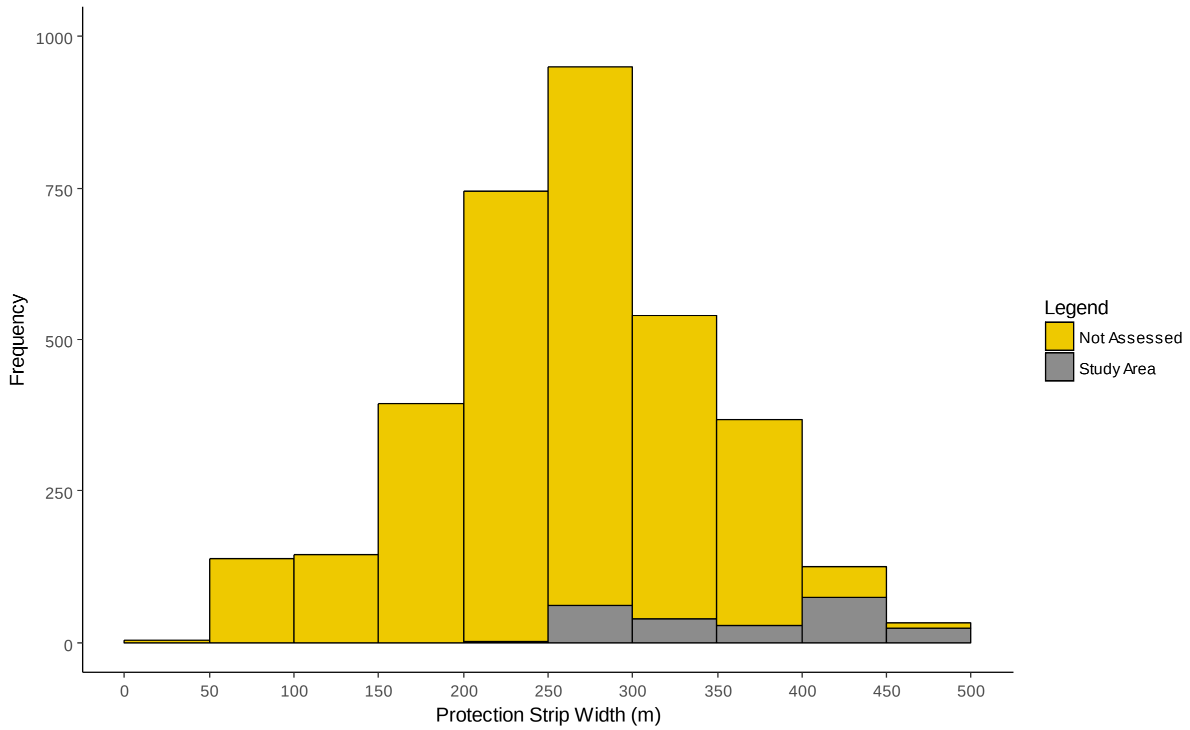

Figure 4.1: Distribution of Woodhill protection strip width, measured at 10m intervals. Grey bars indicate the distribution of widths at the study site.

4.2 Sampling Results

4.2.1 Protection strip

Figure 4.2 shows the results of key measurements in the protection strip. The results are displayed as both boxplots, classified by the plot number, and as scatter plots to display the relationship with distance to the coast. Only two variables were found to have a significant relationship with distance to the coast. The PMH had a marked increase from plot 1 at the coastal edge to plot 3 at the inland edge of the protection strip. ANOVA analysis showed that there was a significant difference between the PMH in each of the 3 plots (p-value $\ll 0.001$). The relationship between protection strip PMH and distance to the coast was found to be logarithmic. A regression of protection strip PMH against the log of distance to the coast found the relationship could explain 85% of the variation in PMH (p-value $\ll 0.001$).

As PMH was the only measurement taken at three locations along each transect, the protection strip data was also examined with plot one values excluded to enable comparisons with other variables. The linear relationship between the distance to the coast and PMH in plot 2 and 3 was found to be significant (p-value $\ll 0.001$); however, the variation explained (29%) is less than variation explained when plot 1 values are included (85%).

The proportion of trees classified as healthy per plot displayed a significant, linear relationship with distance to the coast. For every 100m inland a plot was located, the proportion of healthy trees was expected to increase by 7% (p-value = 0.01). The relationship with distance to the coast explained 13% of the variation in the proportion of healthy trees. A significant difference was also found between the proportion of healthy trees in plot 2 and plot 3 (p-value $\ll 0.001$).

Other variables identified in the literature which can influence the ability of a shelterbelt to provide protection were also measured. Basal area, average DBH, stocking, and crown length were not found to have a significant relationship with distance to the coast (p-value > 0.05). A significant difference was detected between the crown length in plot 2 and in plot 3 (p-values $\ll 0.001$). For all other variables there was no significant difference between plots (p-value > 0.05).

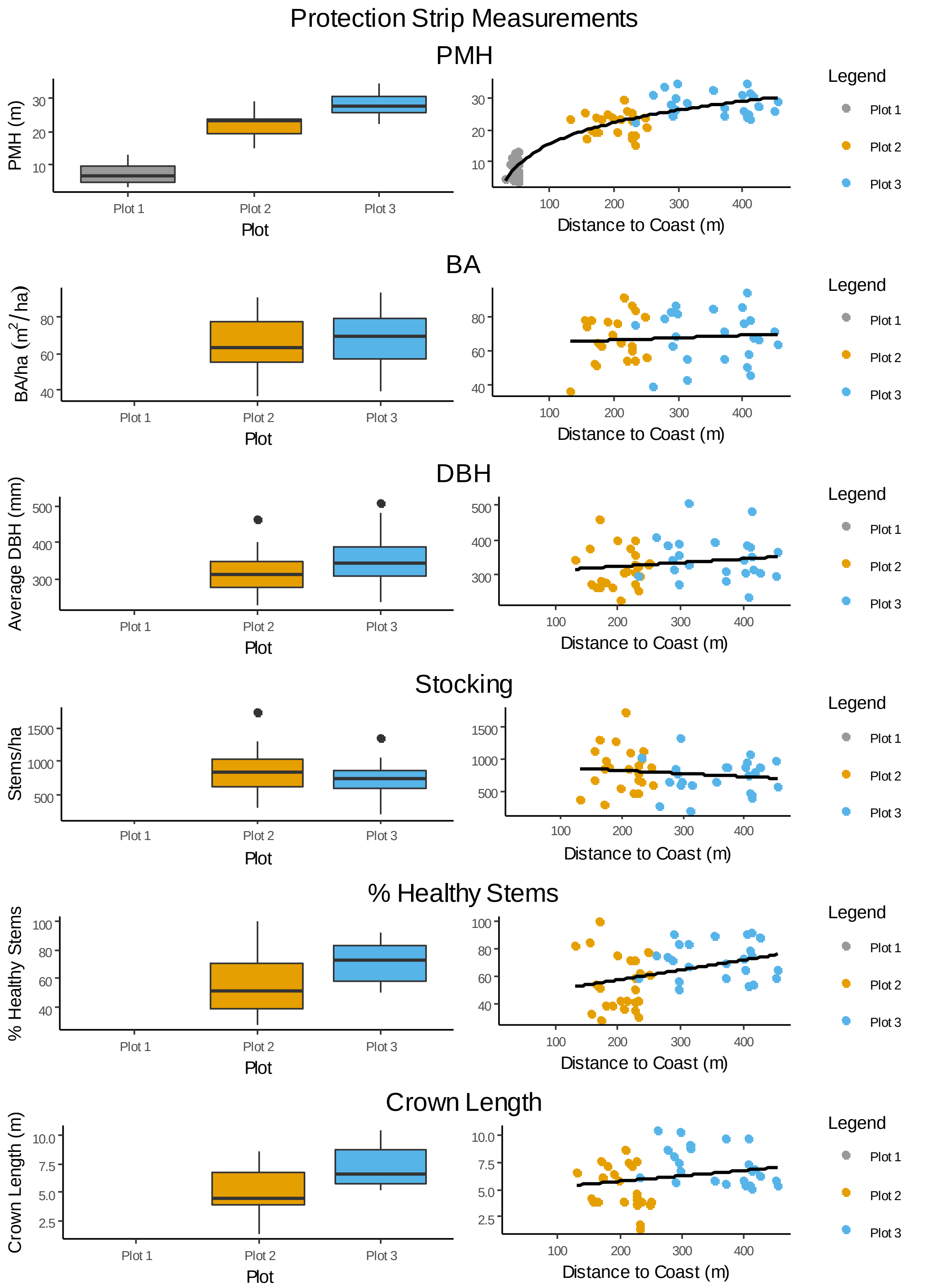

Figure 4.2: Results of the measurements in the protection strip. PMH, BA/ha, average DBH, stocking /ha, proportion of healthy stems, and crown length are shown as boxplots according to plot number (left hand side) and with reference to the distance to the coast (right hand side). The relationship between distance to the coast and PMH is shown as a logarithmic relationship, all others are shown as a linear relationship.

4.2.2 Production stand

The results of the sampling in the production stand suggested that the relationships observed in the protection strip (Figure 4.2) were not present in the stand. No significant relationship was found between the distance to the coast and the measured variables in the production stand (Figure 4.3). Furthermore, no significant difference was found between plot 4, plot 5 and plot 6 values for PMH, basal area, average DBH, stocking, proportion of healthy stems per plot, or volume ($p\text{-value} > 0.05$). In the production stand, the proportion of healthy stems was consistently higher than in the protection strip and only 8 plots (out of 72) were found to contain poor or dead trees.

The results indicated that that the variability was greater closer to the protection strip. Variation in plot 4 basal area, PMH, and volume was greater than that in plot 5 and 6. The standard deviation of plot 4 volume was 63.7m^3/ha compared to 55.1 m^3/ha and 36.8 m^3/ha in plot 5 and 6 respectively.

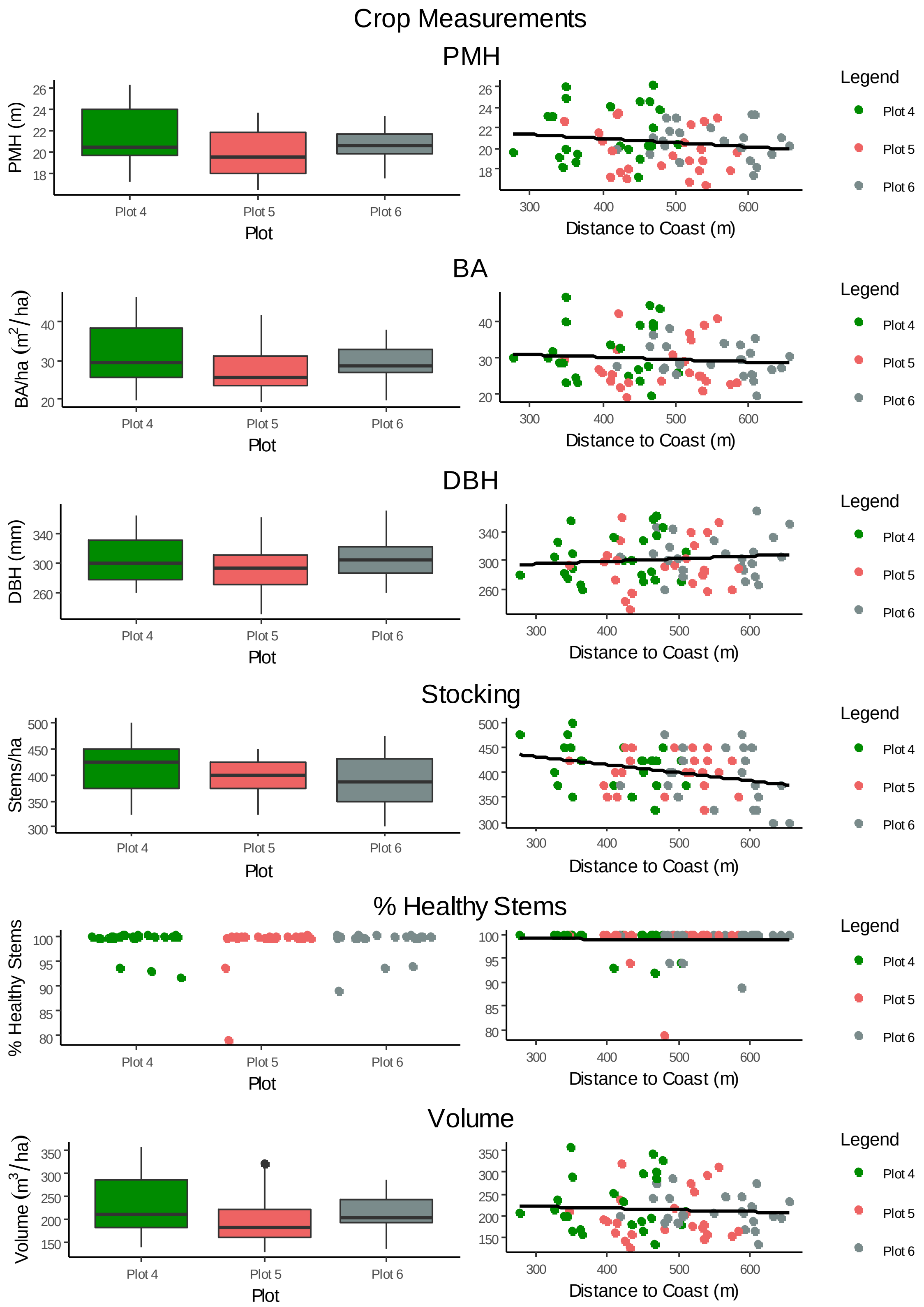

Figure 4.3 Results of the measurements in the production stand. PMH, BA/ha, average DBH, stocking /ha, proportion of healthy stems, and volume/ha are shown as boxplots according to plot number (left hand side) and with reference to the distance to the coast (right hand side).

4.3 Shelter Variables

Previous analysis in the literature of shelter provided by shelterbelts suggested that the width, height, density, porosity, and crown length of the Woodhill protection strip could all influence the productivity of the stand behind. These factors and related variables were compared with the stand volume in all three production stand plots. The correlations between variables and stand volume by plot can be found in Table 4.1.

Two variables were found to have a significant correlation with plot volume. Plot 3 PMH adjusted for topography (r = 0.56, p-value = 0.004) and health score (r = 0.41, p-value= 0.009) were both significantly correlated with plot 4 volume only. No variable was found to have a significant correlation with plot 5 and plot 6 volume (p-values > 0.05).

These two variables were combined to create a shelter variable. The shelter variable was found to have a significant correlation with volume of plot 4 (r = 0.65, p-value = 0.0006). Basal area was also found to have a moderate correlation with plot 4 volume; however, it was not deemed to be significant (r = 0.36, p-value = 0.08) and could not explain additional variation when added to the shelter variable.

Table 4.1: Correlation coefficients between production stand volume and protection strip variables.

Variable	**Correlation coefficient**		
	Plot 4	Plot 5	Plot 6
Width	0.08	0.07	-0.23
Average Stocking	-0.15	-0.05	-0.19
Crown Angle	0.06	-0.18	0.05
Plot 3 Average DBH	0.25	-0.14	0.02
Plot 3 Porosity (Formula 1)	-0.16	0.16	0.25
Plot 3 Crown Length	0.14	-0.12	0.04
Plot 3 Basal Area	0.36	0.13	-0.11
Plot 3 Health Score (Formula 3)	0.41*	0.40	0.22
Plot 3 PMH (adjusted for topography)	0.56**	0.14	-0.22
BAxPMHxHS	0.64***	0.33	-0.09
Shelter (PMHxHS) (Formula 4)	0.65***	0.42*	<0.00

** significant at p<0.05, ** significant at p<0.01, *** significant at p<0.001*

4.4 Protection Strip Shelter

The shelter variable was found to have a significant relationship with volume in both plot 4 and plot 5 (Figure 4.4). Shelter was able to explain 42% of plot 4 variation in volume (p-value = 0.0006). The relationship predicts that a unit increase in shelter results in an increase of 8.5m^3/ha. The relationship could only explain 18% of the variation of volume in plot 5 volume (p-value = 0.04) and for a unit increase in shelter, the volume of plot 5 is predicted to increase by 4.8m^3/ha. The relationship between the protection strip shelter and volume in plot 6 was found to be not significant (Figure 4.4). A summary of the models can be found in Table 4.2.

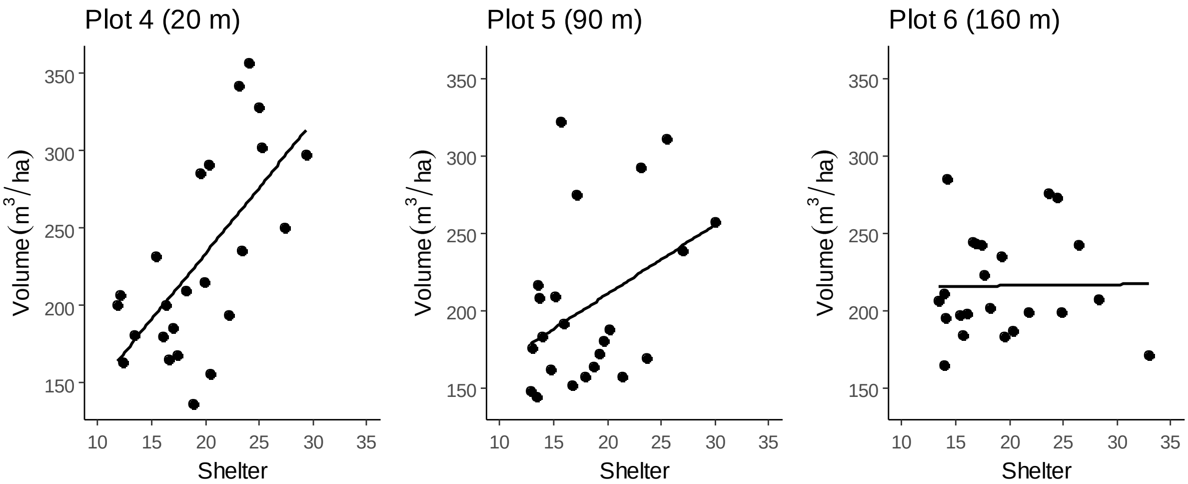

Figure 4.4: Relationship between "Shelter" (protection strip inland edge (plot 3) PMH (less the elevation difference between strip and stand) multiplied by the Health Score) and stand volume by plot

Table 4.2: Results of the model predicting stand volume using protection strip shelter

	Plot 4	**Plot 5**	**Plot 6**
Intercept	63.8	112*	213***
Shelter coefficient	8.50***	4.83*	-0.05
Residual standard error	49.6	51	37.5
R-squared	0.42	0.18	0.00
P-Value (overall model)	0.0006	0.04	0.98

** significant at p<0.05, ** significant at p<0.01,*** significant at p<0.001*

The relationship seen in Figure 4.4 between protection strip shelter and plot 4 and plot 5 volume could be the result of other abiotic factors, such as fertility, having an underlying influence on both plot 3 shelter and stand volume. To account for the confounding effect this may have on the results, plot 6 volume was added to a model as another independent variable with shelter to predict stand volume in plot 4 and 5. Plot 6 volume was found to have a low correlation with protection strip shelter (0.13) but a higher correlation with plot 4 (0.18) and plot 5 (0.52) volume. It was reasoned that the similarities between plot 4/5 and plot 6 could not be attributed to influence from the protection strip.

When plot 6 volume was included as a variable in the model, the relationship between shelter and volume were still found to be significant, suggesting that shelter accounted for a proportion of variation in plot 4 and plot 5 volume (Table 4.3). In plot 4, the relationship showed an increase in a unit of shelter would result in an increase in 8.3m^3/ha (p-value = 0.001). In plot 5, the relationship suggested that an increase in a unit shelter would result an increase of 4.7m^3/ha (p-value = 0.02). The results of the model with plot 6 as an additional variable is very similar to the original model without plot 6. Due to the significance of the relationships when plot 6 is included in the model and the similarities with the original model above, there can be confidence that the relationship between plot 4 and 5 volume and plot 3 shelter is a result of the shelter effect rather than only underlying site conditions.

Table 4.3: Results of the model predicting stand volume using protection strip shelter and plot 6 volume

	Plot 4	Plot 5
Intercept	29.4	-47.5
Shelter coefficient	8.34***	4.71*
Plot 6 volume coefficient	0.17	0.76**
Residual standard error	50.3	43.3
Adjusted R-squared	0.38	0.38
P-value (overall model)	0.003	0.003

** significant at p<0.05, ** significant at p<0.01,*** significant at p<0.001*

4.4.1 Distance to coast relationship

The volume of the stand was not found to have a significant relationship with the width of the protection strip in any of the plots. Figure 4.5 shows that increase in strip width between 280m and 460m is inconsequential on the volume of the stand, regardless of the distance from the protection strip.

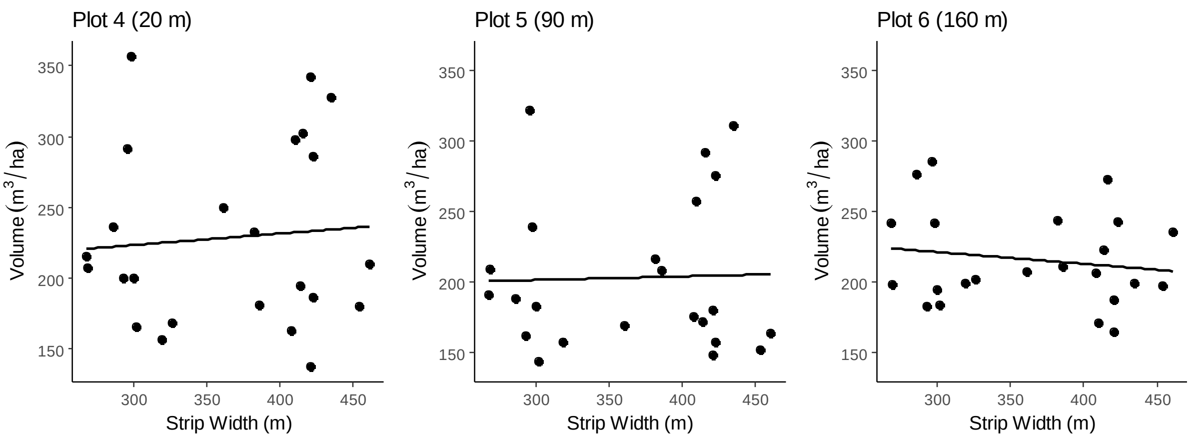

Figure 4.5: Relationship between protection strip width and the stand volume by plot

The plot 3 shelter variable was not found to have a significant relationship with distance to the coast. However, if plot 2 was included, a significant relationship could be detected (p-value < 0.001). The relationship seen in Figure 4.6 suggests that for every 100m inland, the shelter variable would increase by 3.5 units. There was high variation around this relationship, with an r^2 of 0.25. However, it does suggest that the protection strip width is important where the strip is particularly narrow. The results of the model predicting protection strip shelter using distance to coast are shown in Table 4.4.

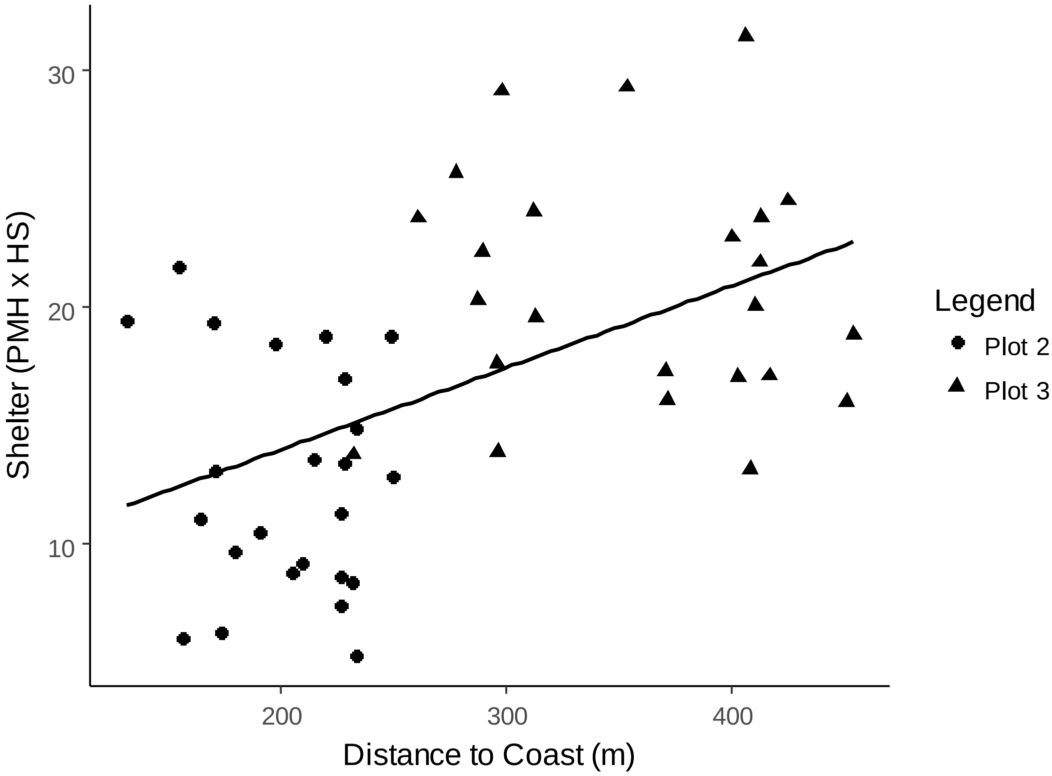

Figure 4.6: Relationship between distance from the coast and plot 2 and plot 3 PMH x HS in the protection strip.

Table 4.4: Results of the model predicting protection strip shelter using distance to the coast.

	Protection Strip
Intercept	7.09**
Shelter coefficient	0.03***
Residual standard error	5.60
R-squared	0.25
P-value (overall model)	0.0003

** significant at p<0.05, ** significant at p<0.01,*** significant at p<0.001*

Chapter 5: Discussion

The results of the protection strip sampling allowed for a shelter variable to be created. The literature suggested that the height (McAneney et al., 1990) and the porosity (Cornelis & Gabriels, 2005) of the protection strip would be key determinants of shelter. PMH was found to have a strong correlation with stand volume (Table 4.1) and was included in the shelter variable. Porosity was not directly measured and could not be included in the shelter model. Yang et al. (2017) provided a method to calculate porosity using remote sensing (Formula 1); however, this was not found to be significantly correlated with stand volume (Table 4.1) and was not included in the shelter variable. Basal area and stocking, measured variables similar to porosity, were also not found to be significantly correlated with stand volume and not included in the shelter variable (Table 4.1). Protection strip condition, as measured by the health score, was found to explain additional variation when included as a factor in the shelter variable. It can be concluded that the protection strip height and condition are two determinants of shelter in Woodhill Forest, and have been found to have a significant relationship with stand volume close to the strip edge.

Both the height and the condition of the protection strip improve moving inland from the coast. The poor size and condition of trees close to the coast is similar to observations made previously in Woodhill Forest. Berg (1972) suggested a gradient in 23-year-old *P.radiata* tree height with increasing distance to the coast similar to that found in this study. Berg also noted tree damage in reference to distance from the coast. As both variables were used to explain shelter, the relationship emphasises the need for the maintenance of the protection strip, particularly as the condition declines.

The protection strip is primarily in place to protect against the impacts of strong winds and the salt they can carry. Management of the protection strip should consider how the strip shelters against these and how this may change in the future.

5.1 Shelter

5.1.1 Wind speed reduction

Although not tested in this study, the conclusions from the literature can provide suggestions as to the pattern of wind speed around the Woodhill protection strip. A typical length where wind speed is reduced was reported to be 30H (Caborn, 1957). The average PMH at the inland edge of the protection strip was between 28m, suggesting a theoretical shelter distance of 850m. However, features of the Woodhill protection strip mean the wind abatement length would be shorter than what is typical behind a shelterbelt. The Woodhill protection strip is distinct from the shelterbelts described in the literature due to the extreme width and gradient in tree height. A greater width and sloped canopy are characteristics which cause the location of minimum wind speed to move closer to the barrier providing shelter (Caborn, 1957). It is likely the Woodhill protection strip has a restricted length of impact due to these factors.

The Woodhill protection strip also differs from most shelterbelts as it protects a production forest rather than agricultural or horticultural crops. A forest can be expected to interact differently with a shelterbelt over time compared to other production systems. As the productive forest behind the protection strip grows, it is likely that it will also begin to deflect wind over the canopy, acting as an extension of the protection strip. This phenomenon will likely only occur in the later ages of the stand's life when the stand canopy closure provides a barrier to the wind. Therefore, it can be concluded that the most important role of the protection strip is to shelter young stands, and to help establish and protect the stand edge.

At early ages, before canopy closure, the stand will be similar to that of agricultural and horticultural crops cited in the literature. The stand will be influenced by the reduction of wind and the altered microclimate. However, the pattern of growth behind a shelterbelt, as suggested by the literature (e.g. Campi et al. (2009)) was not observed at Woodhill Forest. No significant difference in volume was found between any of the plots in the production stand. It is not possible to assess if this was due to the stand never growing in the reported pattern, or if growth evened out over time. It is also not possible to conclude if the shelter provided to young stands increases net productivity without assessing an area with no protection strip present.

The protection strip height and condition were shown to have a correlation with the stand edge volume (Figure 4.4). The presence of the protection strip enables the coast edge of the stand to establish without the continued exposure to coastal winds which have been attributed to damage in the protection strip. In allowing the stand edge to establish, the interior of the stand is provided a degree of protection from the stand itself. Although the implications of not having a protection strip are not clear without comparisons to an area without the presence of the protection strip in Woodhill Forest, the absence of any shelter would likely have significant implications for stand quality. Likewise, the stand edge would likely experience significant damage from the impacts of coastal exposure.

5.1.2 Wind driven salt protection

The gradient in the height of the Woodhill protection strip could be attributed to the presence of wind driven salt from the Tasman Sea. The damage on the coastal edge of Woodhill Forest is comparable to that of other coastal forests reported by Potts (1978). Although salt was never directly measured, Berg (1972) reported stunted growth and damage in Woodhill Forest which was attributed to the effects of wind driven salt. According to Berg (1972), severe damage to stems could extend as far as 100m into the forest. In comparison Potts (1978) found salt damage was typically only within 5m of the forest edge. This study in Woodhill Forest found a significant gradient in average tree height and condition with distance to the coast. Presence of salt has previously been shown to influence tree condition and growth. Visible needle damage in tree needles occurs at concentrations over 1mg/g of chloride in tree needles (Aamlid & Horntvedt, 2002), while sea salt used for road de-icing has been attributed to a reduction in annual growth of trees close to a highway (Hall, Hofstra, & Lumis, 1972). The presence of sea salt concentration in conifer needles has been found to have negative, logarithmic relationship with distance to the coast (Aamlid & Horntvedt, 2002). These results suggest that gradient of tree height and condition in the protection strip can be attributed, in some part, to the presence of wind driven sea salt. If the protection strip was not present it would likely have a significant impact on the size and quality of the production stand.

However, there is no suggestion that salt is having a similar impact on the stand behind the protection strip. No gradient in tree growth or health was detected with distance to the coast, or distance to the shelterbelt. The salt-distance to coast relationship estimated by Aamlid & Horntvedt (2002) in Norwegian forests suggests that within 1km of the coast, salt concentration is high enough to cause visible damage to needles. Furthermore, annual sea salt deposition in New Zealand was found to be significantly higher at comparable distances than reported values from other countries (Ballance & Duncan, 1985), suggesting that if no protection strip was present, the effects of salt on the growth and health of the production stand would be detectable. The lack of such damage means that the protection strip is providing the service it was left to do.

The protection strip was established to reduce the amount of wind driven salt damaging the remaining forest. Air borne salt can be reduced both through reduced wind speed (Koricheva, Larsson, & Haukioja, 1998; Zhu et al., 2002), and through filtering of salt in the foliage (Zhu et al., 2002). As discussed above, the protection strip height and condition show a correlation with stand volume. Crown length, a measure of foliage in the protection strip, did not show any significant correlation with stand volume (Table 4.1). However, crown length was measured only on trees which were also measured for PMH. Height trees were selected according to the largest diameter, and often the largest trees would be of good health. Consequently the crown length measure does not consider the lack of foliage on poor health or dead trees. The health score, a measure of the number of trees with varying degrees of foliage, was shown to have a moderate correlation with plot 4 volume. The health score could be a better estimate of the amount of foliage present in the protection strip, and thus the ability to filter salt. Where the protection strip has experienced high mortality, the stand could be exposed to higher degrees of air-borne salt.

5.1.3 Future shelter requirements

The need for a protection strip in Woodhill Forest may increase in the future as there is potential for the effects of climate change to increase wind damage in New Zealand forestry plantations. A warmer climate is expected to produce taller and more slender trees, increasing the susceptibility to wind damage (Moore & Watt, 2015). An increased susceptibility means a lower critical wind speed is required for tree damage (Moore & Watt, 2015). While critical wind speed for forest damage can be expected to decrease, wind speed in New Zealand is expected to increase with climate change. The frequency of strong winds (>10m/s) are predicted to increase with warmer climates (Ministry for the Environment, 2008). Westerly winds, which bring air-borne salt from the Tasman Sea to Woodhill Forest, has been predicted to have the greatest increase in New Zealand, with a 10% increase in strong winds over the next 50 years (Ministry for the Environment, 2008).

In Woodhill Forest, an increase in wind speed may cause damage to the forest through both direct wind damage, and salt induced damage. Above 5m/s, the concertation of air-borne salt is linearly related with wind speed (Lewandowska & Falkowska, 2013; Zhu et al., 2003). Currently, the median wind speed in Woodhill Forest is less than this critical 5m/s speed (NIWA, 2012) and it is likely that the forest is only exposed to wind-driven salt in high wind events. Climate projections suggest the frequency of salt damage will increase in Woodhill Forest, placing more importance on the protection strip in the future.

5.2 Management Implications

5.2.1 Standard width

The protection strip plays a key role in the success of Woodhill Forest. Without it, it can be assumed that production trees would be exposed to the influence of salt-laden coastal winds, and productivity will be reduced. However, the results of this study suggest that the protection strip width could be standardised to a consistent width. The relationship between the shelter variable and the distance to the coast, seen in Figure 4.6, was relatively weak (r^2=0.25) and suggested that at widths over 250m, changes in the protection strip width would not significantly reduce the shelter provided. Furthermore, no relationship was found between protection strip width and the volume in the stand behind (Figure 4.5), meaning that any reduction in protection strip width would not likely influence volume on a per hectare basis but could provide an increase for potential planting area.

The minimum width of the protection strip measured by a transect at the study site was 277m and the protection strip at this width was found to provide sufficient protection to the stand behind. Furthermore, the relationship between protection strip height and log distance to the coast (Figure 4.2) suggests that the protection strip height will not increase significantly with width beyond a distance of 277m from the coast. The relationship predicts that only a 5m difference in protection strip height can be expected between a protection strip width of 277m and 461m (the maximum width measured). Assuming that the protection strip at the site used for this study is representative of the entire protection strip, it can be reasoned that the protection strip could be standardised to a 277m width for the entire length without significant impacts to the quality of the stand. In its current state, the protection strip width varies between 50m and 500m (Figure 4.1). If the protection strip was to be standardised to a constant width of 277m, the total area of the protection strip would be reduced by 458ha, resulting in a decrease in protection strip area of 29%. The area removed from the protection strip could be planted as productive land, increasing the net stocked area of the forest without sacrificing protection provided by the protection strip.

5.2.2 Improving the Woodhill protection strip

The correlation between protection strip shelter and plot 4 volume suggests that where protection strip shelter can be improved, the volume at forest edge, and potentially further in, will increase. If one of the components of shelter (tree height or health score) was increased, a greater volume can be expected in the adjacent stand. Furthermore, the greater the quality of the stand edge, the greater it will be able to provide protection to the remaining stand. Berg (1972) recommended the use of macrocarpa as a shelter species in Woodhill Forest as it was found to be better performing than *P.radiata* close to the coast. Average tree height of macrocarpa was greater than *P.radiata* at distances between 25m and 175m from the coast edge in 23 year old trees (Berg, 1972). Berg (1972) also reported less malformation in macrocarpa trees than was observed in *P.radiata*. Although some rows of macrocarpa trees can be found in Woodhill Forest, the species does not appear to have been widely utilised. Macrocarpa has the potential to have a higher shelter value closer to the coast than what is achieved with *P.radiata*. The use of the more salt tolerant species could allow for greater protection at the back of the protection strip, which is correlated with stand growth. Alternatively, a macrocarpa protection strip could achieve the same level of shelter closer to the coast, allowing for a narrower strip and greater net stocked area.

Improving the Woodhill protection strip may also reduce the damage caused by forest pests and diseases as well as coastal exposure. Stressed or dead trees in the protection strip could provide habitat for unwanted forestry pests and provide a pathway for pests to the nearby production forest. Stress levels in trees has been reported to increase the performance of wood boring and sap sucking insects in forests (Koricheva et al., 1998), increasing the potential of a successful population establishing. Furthermore, shelterbelts have previously been suggested as “stepping stones” for forestry pests. *Hylastes ater* (bark beetle) have been recorded in declining shelterbelts, absent of their typical habitat (logging slash) which has enabled their dispersal to production forests (Be, Chase, & Brockerhoff, 2017). The relatively poor health of the protection strip could allow the build-up in population of these pests, which could subsequently cause damage to the production stands.

5.2.3 Remote sensing for surveillance

The Woodhill protection strip is extensive and monitoring the condition over the entire 41km length with manual sampling, such as that used in this study, is impractical and costly. Yang et al. (2017) proved remote sensing was a viable method for gathering useful information on shelterbelt performance. Although the method reported by Yang et al. (2017) was not found to provide an explanation of stand growth in Woodhill Forest (Table 4.1), there is potential for a similar process to be created which would allow rapid measurement of the protection strip. Measurements of protection strip height and condition from remote sensing could be used to provide an indication of the quality of the protection strip along the entire length. This could also allow for repetitive monitoring of the strip over time. Quick and repetitive assessments will provide important information required in maintaining the protection strip as it ages.

5.3 Limitations of the Study

5.3.1 Representative site

To draw conclusions from the results of this study it needs to be assumed that the protection strip and production stand where the study was undertaken are representative of other locations along the coast. The initial mapping of the protection strip with aerial photography indicated that although the protection strip was wider than the median strip width (Figure 4.1) the study location was similar in tree health and cover to other areas of the protection strip. However, without comparisons to other sites, it cannot be stated with complete confidence if this site is typical of the protection strip and adjacent stands in Woodhill Forest.

5.3.2 Site influence

The investigation into the relationship between protection strip shelter and stand volume in Woodhill Forest did not directly measure fertility and other site influences. Such aspects have the potential to be the underlying reason for the correlation between plot 3 shelter and plot 4 and 5 volume. Due to the proximity of these plots, it can be assumed that site conditions are similar, which would likely result in similar levels of productivity. Plot 6 volume, which showed a low correlation with shelter, was included as another variable in the model. The resulting significant relationship seen between shelter and volume (with plot 6 as a covariate) meant that some confidence can be had that the volume is correlated with stand shelter however, the degree of this cannot be confirmed. To provide a more accurate representation of the relationship between the protection strip and stand volume, measurements incorporating site influences are required.

5.3.3 Long term shelter

This study only measures the protection strip and stand at one point in time. With the time available it is not possible to measure the protection strip and the stand through the length of a rotation. It has therefore been assumed that the current estimate of shelter received by the stand is representative of the last 16 years. In reality, the protection strip size and condition are constantly changing. The two key determinates of shelter, protection strip height and health score, are likely to change with age as it can be expected that both tree height and mortality will increase over time. It can therefore be assumed that the shelter provided will have changed too.

5.3.4 Protection strip porosity

Porosity was reported to be a key determinant of the ability of a shelterbelt to provide shelter (e.g. Cornelis & Gabriels (2005)). The difficulties in directly measuring porosity have led to several methods of estimating variables similar to porosity (e.g. optical porosity). However, many of these methods were not appropriate for the Woodhill protection strip due to the extreme width. Measuring porosity through vehicle mounted lasers, as suggested by Lee et al. (2010), was not undertaken due to the unavailability of specialist equipment. An estimate of porosity was provided using function of LAI, crown length, and protection strip width from remote sensing, as suggested by Yang et al. (2017) was calculated. The resulting porosity estimate was not shown to have a relationship with stand volume, with a low correlation coefficient (-0.16). It was therefore not included in any value of shelter. However, the porosity calculation may not have been an accurate measure of true porosity. The LAI values were derived from multispectral imagery only, and the reliability of the values were not confirmed with measurements. Furthermore, there was no validation of the technique in the Woodhill protection strip, where conditions differ from a typical shelterbelt, and the reliability of the values to accurately represent porosity is not known.

The variable similar to porosity which showed the strongest relationship with stand volume was basal area. Basal area can be considered the area of space filled in a horizontal plane, while porosity can be considered the area of space filled on the vertical plane. The relationship between basal area and porosity would change depending on the spatial arrangement of trees in the protection strip. Basal area was shown to have a moderate correlation with stand volume (Table 4.1) but was not included in the shelter model as it was not able to increase the variation explained by the shelter variable. If porosity was contributing to shelter in the protection strip, the inability to accuracy measure or predict porosity may mean that the true relationship between the protection strip shelter and stand volume cannot be estimated.

5.3.5 Protection strip width

It is not possible to conclude the degree to which the protection strip provides shelter, and its relationship with stand volume, without measuring a production stand in areas where no protection strip is present. There was no location within Woodhill Forest where the protection strip was not present to undertake this investigation. Furthermore, areas where the protection strip was narrower were unsuitable for this analysis due to the production stand area or age restricting suitable measurements. Such research may be suited to wind tunnel analysis, which was shown by Caborn (1957) to accurately represent in-situ shelterbelts. Testing the extremes of width, and other variables, in a wind tunnel may allow for more confident results to be concluded about the degree to which the protection strip improves the forest, and the optimal width of the protection strip. Utilising a wind tunnel would also allow for analysis without the potential influence of site conditions confounding the results.

Chapter 6: Conclusion

This research aimed to investigate how the Woodhill Forest protection strip sheltered production stands from salt laden, coastal winds which hamper the growth of trees on the westerly side of the forest. In doing so the research focused on answering if the production stand volume is related to characteristics or the width of the protection strip, and how the quality of the protection strip could be assessed. It was found that the production stand volume was related to the protection strip height and health, but not the protection strip width. This information can be used to assess the quality of the protection strip throughout the forest.

The height (minus the difference in elevation between the protection strip and the stand) and health of the protection strip were found to show the strongest correlation with stand volume of all the variables investigated (Table 4.1). Combined, these two variables created a shelter variable able to explain 42% of the variation of volume of the stand within 20m of the protection strip (Figure 4.4). The relationship between the protection strip and the stand volume reduced with increasing distance from the protection strip. By 160m from the strip no significant relationship between strip characteristics and stand volume was detected. However, it can be assumed that the trees at the stand edge, and deeper into the stand, are providing shelter to the remaining stand directly behind.

Although site conditions were retrospectively considered during this analysis, it is not possible to accurately assess the influence of these on the relationship between protection strip characteristics and stand growth with the information available. The inland edge of the protection strip and the first plot measured in the stand are close enough to assume that site conditions, such as fertility and water availability, are similar. Although the results do suggest that shelter provided by the protection strip can explain some variation of stand growth (Table 4.3), it cannot be stated how much is due to the underlying site conditions.

The protection strip width was not found to be significantly related with the volume of the stand (Figure 4.5), meaning the size of the protection strip may not be optimising the net productivity of the forest. The relationship between protection strip height, which was used as a component of the shelter variable, and the distance to the coast plateaued when distance to the coast was approximately 250m (Figure 4.2). This suggests that at greater distances than this, the protection strip width will not greatly influence the shelter provided to the stand. Furthermore, the stand volume behind the protection strip at a width of 277m, the minimum protection strip width measured in this investigation, was not found to be reduced from that compared to greater widths (Figure 4.6). It is inferred that standardising the protection strip width to 280m would not significantly impact the performance of the stand. Doing so would reduce the protection strip area and provide more area for production stands in the future.

The protection strip height and condition can be used to assess the quality of the protection strip in other areas. Understanding where the protection strip may not be providing sufficient shelter or is deteriorating in quality, particularly at the inland edge, can help in future management of the protection strip. This will be of increasing importance as the protection strip ages, particularly as the potential for increased damage can be expected due to changing climatic factors. The forest has a long, exposed edge and quick assessment of the shelter provided to the forest will be vital during future management of the protection strip. It is suggested that remote sensing could provide a rapid method for repetitive assessment of the protection strip to ensure the quality of the stand is not impacted by a lack of shelter.

Further research could also aid in the management of the Woodhill protection strip. Conclusions on the influence of width in this study are limited to the range investigated. It was shown that 280m was wide enough to ensure adequate growth of the stand behind, but it is not possible to state at what point the width of the protection strip becomes too narrow to provide the necessary shelter. Repetition of a similar investigation at sites with a narrower protection strip could provide an indication as to the minimum width where the protection strip still provides sufficient shelter to the stand behind. Similarly, the use of a wind tunnel could allow for a more in-depth analysis to be undertaken, without the potential for site influence to confound the results.

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Appendices

Appendix 1: Height Diameter Relationship

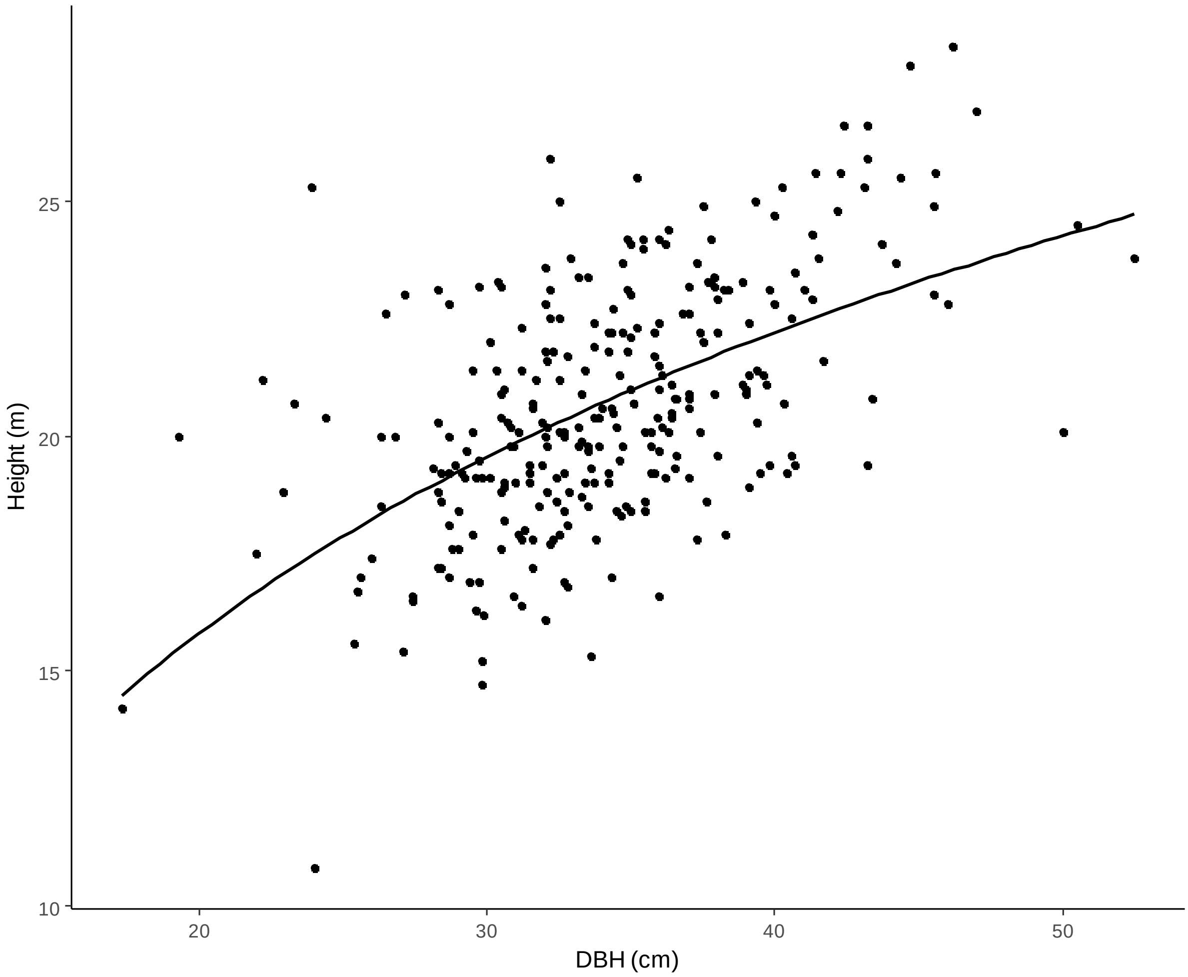

Figure A1: Protection strip tree height (m) diameter (cm) relationship

Table A1: Results of the model predicting protection strip tree height (m) using protection strip tree diameter (cm). The intercept and log (DBH) coefficient were used in the volume calculation (Formula 2)

Intercept	-11.8***
Log (DBH) coefficient	9.23***
Residual standard error	2.21
R-squared	0.30
P-value (overall model)	$2.2x10^{-16}$

** significant at p<0.05, ** significant at p<0.01,*** significant at p<0.001*